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Using 7Be to Trace Temporal Variation of Interrill and Rill Erosion on Slopes

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Abstract

Understanding the processes of erosion-transport-deposition of sediments is necessary to develop more effective soil erosion prediction models. In this study, Beryllium-7 (7Be) was used as a tracer to describe the dynamics of soil erosion during a simulated rainfall event on outdoor cultivated plots. The quantitative results of interrill and rill erosion on slopes are discussed in this paper. And the calculated results using 7Be tracer are in good agreement with the measured ones. Therefore, 7Be tracer could accurately quantify the processes of erosion on the cultivated slope.

Keywords: Be tracer; Interrill erosion; Rill erosion; Contributions; Cultivated plot

1. Introduction

Slope erosion is a very complex process. After the processes of erosion-transportation-deposition, sediment partially deposits at the flat foot area of the cultivated slope, and a small deposition area is formed [1-2]. Interrill and rill erosion appears successively and the deposition in the flat foot area may from interrill and rill erosion. Understanding of the erosion-transportation-deposition processes is the key for the development of physically-based erosion prediction models. However, traditional erosion monitoring techniques do not provide enough information to partition the sediment from interrill and rill erosion. Several frequently used physically-based erosion models, such as WEPP, LISEM and EUROSEM do not separate the timing of the transition from interrill to rill erosion and the relative contributions of the two processes during individual rainfall event. Furthermore, in the foot area of the slope, the models do not distinguish the deposition from interrill and rill erosion. Use of ^{7}Be, as a soil erosion tracer, can provide further information on the details of soil erosion at specific locations.

^{7}Be is a short-lived radionuclide, with a half-life of 53 days, and is of natural origin. It is produced in the upper atmosphere by the spallation of nitrogen and oxygen by cosmic rays. Then it diffuses through the

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atmosphere until attaches to an atmospheric aerosol. Subsequent deposition at the land surface occurs as both wet and dry fallout. In most environments, ^{7}Be fallout that reaches the soil surface will be rapidly and strongly fixed by clay particles in the surface soil and its occurrence is restricted to a shallow surface layer of 20 mm with a main distribution in the upper 10 mm [3-4]. Since interrill erosion occurs in the upper 1.0 cm of the soil, ^{7}Be can be used to trace interrill erosion. Several researchers [5-7] have studied soil erosion using ^{7}Be as a tracer, and it has been proved that ^{7}Be can quantify the sources of erosion on slopes [8]. However, very few studies on soil erosion processes have considered the influence of deposition in the foot area during erosion events. Further research is needed to address this topic.

The purpose of this research was to use ^{7}Be as a tracer to partition the sediment from interrill and rill erosion, to analyze their contributions to the total soil loss and deposition in the flat foot area, and to study the temporal variation of soil erosion on slopes.

2. Methods and materials

2.1 The field experiment

Two experimental plots A and B were set up outdoors to effectively receive ^{7}Be fallout in Yangling County, Shaanxi Province, China. The slopes of the plots were 25°. The plots were 5 m long × 2 m wide, and were separated by a plastic board. One side served as the ^{7}Be background area with 5 m long and 0.5 m wide, and the other side was the rainfall area (5 m long × 1.5 m wide). Two flat areas without soil (0.3 m long × 1.5 m wide) were set up using cement and sheet iron on the bottom of the two plots before rainfalls. The two experimental plots were filled with soil taken from the upper 5 cm of a nearby farm. The soil was tamped layer by layer when filling the plot. After filling, the surface 20 cm was layer hand tilled, the clods were broken, and the surface of the slope was smoothed. The bulk density of the surface soil was 1.05 $g{\cdot}cm^{-3}$ which was similar to a tilled field condition. The two plots were placed outdoors for six months without human disturbance in order to receive both wet and dry ^{7}Be fallout. In this period there was almost no wind and erosive rainfall, so the ^{7}Be on the slope distributed uniformly. Three 4 m height side-spray rainfall simulators were used to generate rainfall over the plot. The mean rainfall intensities were 1.04 $mm{\cdot}min^{-1}$ and 1.39$mm{\cdot}min^{-1}$ on plot A and B during the rainfalls, respectively. And the rainfall times were 155 min and 69min on plot A and B for the appearance of rills, individually. Runoff started after 10 min and 5 min after initiating rainfall on the two plots.

2.2 Sampling and laboratory analysis

Before the rainfall, mass depth-incremental soil samples were collected from the background area on the slope using sectioned cores, to characterize the mass depth distribution of ^{7}Be. During the rainfall, plastic containers were used to collect the runoff and sediment at the outlet of each plot. When the first container was full, it was replaced by another container and the time was recorded. The sediment in every container was air dried and weighed. After the rainfall, fifteen soil samples were collected from the slope surface of 1.5 cm in depth using the grid method. And in the foot deposition area, three whole depth sediment samples and all sediment were collected. The volume of every rill on the slope was measured and recorded. All soil samples were taken back to the laboratory, air dried, weighed, ground to pass a 1 mm sieve and placed in clean plastic boxes with similar geometric dimension for ^{7}Be activity measurements. The ^{7}Be activity measurements were done by using a low background with a hyperpure coaxial germanium detector and multichannel digital analyzer system.

3. Results and discussion

3.1 Temporal changes of 7Be activities in sediment

During the rainfall event, the sediment was eroded from the slope by runoff, a part of them deposited at the flat foot area, and another part was taken out of the plot at the same time. Almost no redistribution of sediment happened in the flat foot area. Figure 1 presents the ^{7}Be activities associated with the sediment collected from the outlets of the two plots during the course of the simulated rainfall events.

At the onset of interrill erosion, the soil on the slope surface was peeled layer by layer, and transported out of the plot. In the surface soil, the ^{7}Be activities exponentially decreased with the increase of mass depth (Fig. 2). This result is consistent with other studies [3-4] in the characters of mass depth distribution of ^{7}Be. Thus, with the rainfall time, ^{7}Be activities declined in the sediment too.

The ^{7}Be activities in the sediment from plot A and B decreased to some extent in 92 min and 21 min, and then fluctuated slightly. It indicated that the sediment from interrill erosion decreased and rill erosion obviously appeared. But that time was later 45 min and 11 min than the actual beginning time of rill appeared on the slope which was in the 47 min and 10 min.

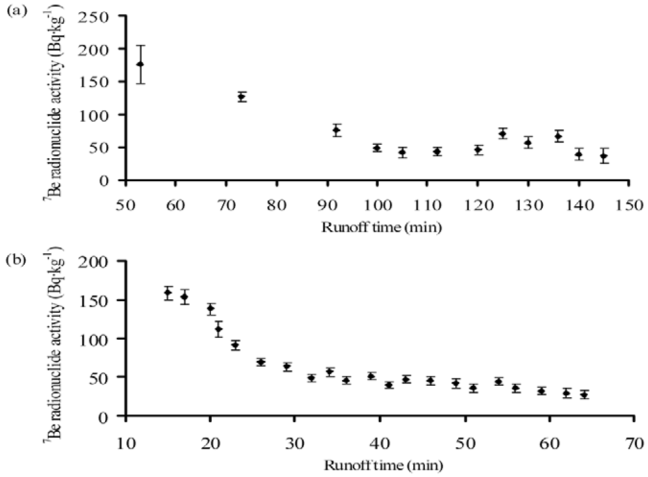

Figure 1. Variation of the 7Be activity of the sediment eroded from the cultivated plots during the simulated erosion event.

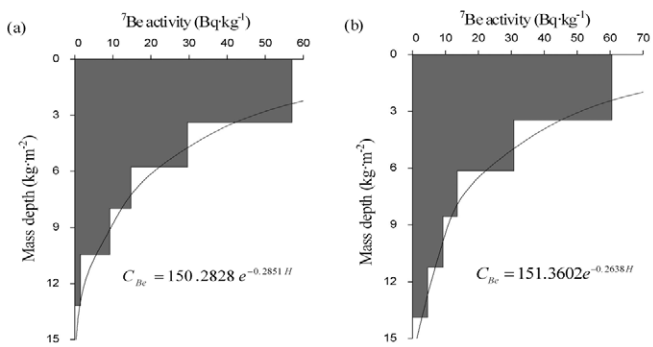

Figure 2. The vertical distribution of 7Be activity in the soil profile within the background area of the plots.

3.2 The relative contributions of interrill and rill erosion

All of the sediment which was taken out of the plot was from the slope, because the flat foot area was bare before the rainfall. A part of the sediment was taken out of the plot, meanwhile another part deposited at the flat foot area. And the deposited sediment didn't redistribute. Although the deposition process of the sediment was not known, the partition of interrill and rill erosion from the total soil loss could be done. Yang et al. [8] proposed the amount of ^{7}Be in the eroded soil can be expressed in terms of a simple mass balance:

$$S \times \int_0^{H_{i,j}} ae^{bH} dH = \sum_{j=1}^{N} W_j \times C_{Be,j} \qquad [1]$$

Where S (m^2) is the area of the experimental plot, W_j(kg) is the mass of sediment collected in the jth time increment, $C_{Be,j}$ (Bq·kg^{-1}) is the ^{7}Be activity in the collected sediment in the jth time increment, $H_{i,j}$ (kg·m^{-2}) is in the jth time increment mean mass depth of interrill erosion in the collected sediment, and the coefficients a and b describe the exponential depth distribution of ^{7}Be in the surface soil layer.

By regression analysis of the ^{7}Be activities in mass depth-incremental soil simples and the mass depth of soil in plot A and B, the relationship can be separately estimated as follows:

$$\text{A plot: } C_{Be} = 150.2828e^{-0.2851H} \quad (n=5, R^2=0.996) \qquad [2]$$

$$\text{B plot: } C_{Be} = 151.3602e^{-0.2638H} \quad (n=5, R^2=0.995) \qquad [3]$$

Where CBe (Bq·kg^{-1}) is the ^{7}Be activities, and H (kg·m^{-2}) is the mass depth of soil.

The mass of interrill erosion in the collected sediment of jth time increment is:

$$E_{i,j} = (H_{i,j} - H_{i,j-1}) \times S \qquad [4]$$

If there is rill erosion on slope, the mass of rill erosion in the collected sediment of jth time increment is:

$$E_{r,j} = W_j - E_{i,j} \qquad [5]$$

Table 1 Changes in the 7Be activity and amount of sediment eroded during the simulated erosion events on the cultivated plots and associated estimates of changes in the importance of interrill and rill erosion during the events

Plot	j	Runoff time (min)	$C_{Be,j}$ (Bq·kg^{-1})	W(g)	$E_{i,j}$ (g)	$E_{r,j}$ (g)
A	1	0-53	176.03±28.39	196	196	0
	2	53-73	127.17±7.08	258	221	37
	3	73-92	75.92±9.77	222	114	108
	4	92-100	49.08±5.30	370	124	246
	5	100-105	42.58±8.38	253	74	179
	6	105-112	43.77±7.41	234	70	164
	7	112-120	46.75±6.75	312	100	212
	8	120-125	71.24±8.66	197	97	100
	9	125-130	57.09±8.48	230	91	139
	10	130-136	67.50±9.36	192	90	102
	11	136-140	40.27±8.90	254	71	183
	12	140-145	36.68±10.61	170	44	126
	Total			T=2888	T_i=1293	T_r=1595
B	1	0-15	158.45±8.76	273	273	0

2	15-17	152.84±9.10	260	260	0
3	17-20	138.01±7.51	331	309	22
4	20-21	112.20±10.23	230	176	54
5	21-23	91.35±6.25	328	206	122
6	23-26	69.36±4.87	633	305	328
7	26-29	63.44±5.15	686	305	381
8	29-32	49.25±4.92	767	268	499
9	32-34	56.88±4.88	889	362	527
10	34-36	46.23±5.22	628	210	418
11	36-39	51.18±4.85	590	220	370
12	39-41	40.02±4.74	672	198	474
13	41-43	47.33±4.82	738	259	479
14	43-46	45.60±5.08	644	219	425
15	46-49	42.49±5.64	567	181	386
16	49-51	36.13±5.20	647	177	470
17	51-54	44.55±4.86	660	224	436
18	54-56	36.17±4.82	837	233	604
19	56-59	32.33±5.42	915	229	686
20	59-62	29.72±5.44	941	218	723
21	62-64	27.69±5.22	511	111	400
		Total	T=12747	T_i=4944	T_r=7803

$E_{i,j}$、$E_{r,j}$ of plot A and B are shown as Table 1. Table 1 indicates that the contributing ratio of interrill erosion gradually decreased with rainfall time, but rill erosion increased. The contributing ratio of interrill and rill erosion fluctuating during the rainfall event may be because of the influence of the changing erosion runoff rate. However, the main trend was that the rill erosion became dominant gradually. After the rainfall, the percents of sediment from interrill and rill erosion were individually 44.8% and 55.2% in plot A, and 38.8% and 61.2% in plot B. These results are consistent with those reported by Yang et al. [8] who found that rill erosion have contributed 54.3% of the total soil loss from the cultivated plot at the end of simulated rainfall.

3.3 Calculation of the interrill erosion on the slope and the deposition in flat foot area after the rainfall

The vertical distribution of the ^{7}Be (Fig. 2) accorded with the exponential distribution hypothesized in the Walling et al. [5] model. So the soil erosion rate R_{Be} (kg·m^{-2}) is calculated as follows:

$$R_{Be} = h = h_0 \ln(A_{Be,ref} / A_{Be}) \qquad [6]$$

Where h (kg·m^{-2}) is the depth of soil loss, h_0 (kg·m^{-2}) is the relaxation mass depth describing the shape of the ^{7}Be depth distribution for an uneroded point, for the exponential distribution h_0 is the 1/e (about 0.37) of the ^{7}Be activities in the upmost surface soil, A_{Be} (Bq·m^{-2}) is the measured ^{7}Be inventory at the sampling point will reflect the depth of soil loss h, and $A_{Be,ref}$ (Bq·m^{-2}) is the local ^{7}Be reference inventory.

If the measured ^{7}Be inventory at the sampling point is larger than the local ^{7}Be reference inventory, deposition is assumed to have occurred. The deposition rate R'_{Be} (kg·m^{-2}) can be estimated as:

$$R'_{Be} = (A_{Be} - A_{Be,ref}) / C_{Be,d} \qquad [7]$$

Where $C_{Be,d}$ (Bq·kg^{-1}) is the ^{7}Be concentration of deposited sediment.

There was no redistribution on the slope when receiving ^{7}Be natural fallout, thus it could be considered that the ^{7}Be on the slope was distributed uniformly before the rainfall. The analyzed vertical distribution of the ^{7}Be in the soil of the background area on plot A and B, gave h_0 as 6.9 kg·m^{-2} and 7.2 kg·m^{-2}, and $A_{Be,\ ref}$ on the slope as 392.6 Bq·m^{-2} and 438.2 Bq·m^{-2}. $A_{Be,\ ref}$ on the flat foot area was zero, because there was no soil in this area before the rainfall.

The amount of interrill erosion (E_i) which is the sum of two parts is calculated as follows. The first part is the depth of soil loss on slope (h). By analysis of the ^{7}Be activities in the samples from plot A and B after the rainfalls and using Eq.6, h was separately calculated as 0.53 cm and 0.58 cm, namely the mass of interrill erosion was 3.398 kg and 4.340 kg. The second part is the depth of soil loss from h cm to 1 cm in rill area (h ~1). Due to the depth of the interrill erosion in rill area would be 1 cm, so the mass of h ~1 was respectively 1.105 kg and 2.042 kg on plot A and B, which was calculated by using the measured volume of the rills (the section of rills on the slope has a shape likes the letter U, thus they could be approximately calculated using rectangle). So E_i of the A and B slopes was individually 5.043 kg and 6.682 kg.

The amount of deposition in foot areas (D) is calculated as follows. By analysis of the ^{7}Be activities in the samples from the foot area of plot A and B and using Eq.7, the mass of deposition was respectively calculated as 6.683 kg and 4.086 kg. The relative error between calculated and measured amount of deposition was 9.2% and 9.4% individually. The results showed that the Walling model could be used to accurately calculate the deposition rates.

3.4 The relative contributions of interrill and rill erosion to the soil loss, deposition and sediment

Based on the mass balance between eroded soil and sediment, relations among erosion, transportation, deposition and sediment can be calculated. All parameters in Table 2 were calculated using the ^{7}Be tracer results, monitoring sediment, and measuring rill volume.

Table 2 The experimental parameters

Parameters	Values (kg)		The sources of data
	Plot A	Plot B	
T	2.888	12.747	Measured
T_i	1.293	4.944	Calculated by Eq.1, Eq.2, Eq.3 and Eq.4
T_r	1.595	7.803	Calculated by Eq.5
D	6.120	3.734	Measured
E_i	5.043	6.382	Calculated by Eq.6 and measured
D_i	3.750	1.438	$D_i=E_i-T_i$
D_r	2.370	2.296	$D_r=D-D_i$
E_r	3.965	10.099	$E_r=T_r+D_r$
E	9.008	16.481	$E=D+T$

E is the mass of soil loss on the slope, D is the mass of deposition in the flat foot area, T is the mass of sediment out of plot, Ei and Er is respectively the mass of soil eroison from interrill and rill erosion on the slope, Di and Dr is respectively the mass of deposition from interrill and rill erosion on the flat foot area, Ti and Tr is respectively the mass of the sediment from interrill and rill erosion out of the plot.

The amount of rill erosion (E_r) on plot A and B was respectively 3.965 kg and 10.099 kg, and relative error was -12.8% and 10.9% compared with measured values (4.548 kg and 9.105 kg, which were calculated using the rill volume below the depth of 1-h cm).

From Table 3 the contributions of interrill erosion to the soil loss, deposition in the flat foot area and the sediment from the plot can be calculated. The percents of interrill and rill erosion in these three parts of plot A were 56.0%、61.3%、44.8% and 44.0%、38.7%、55.2%, and on plot B they were 38.7%、38.5%、38.8% and 61.3%、61.5%、61.2%. It can be concluded that, although the rainfall time of the A plot was longer than the B plot, the contributions of rill erosion to the total soil loss, deposition in the foot area and sediment from the plot on the A plot were smaller than on the B plot, because the smaller rainfall intensity.

4. Conclusions

In this paper, using the distribution of ^{7}Be in surface soil, the sediment out of plots from interrill and rill erosion was quantitatively partitioned by analyzing ^{7}Be activities in the sediment. The results of rainfall on two plots showed that the contributions of interrill erosion in the sediment gradually declined but rill erosion increased. Furthermore, the majority of sediment from rill erosion on plot A and B was respectively delayed for 45 min and 11 min to move out of the plots because of deposition in the flat foot areas.

The calculated mass of rill erosion and deposition based on the sediment mass balance were similar to the measured values. Thus contributions of interrill and rill erosion could be accurately partitioned to the soil loss, deposition in the flat foot area and the sediment from the plot by the method which integrated ^{7}Be tracer, monitoring sediment, simulating rainfall and in-situ measurement.

In a word, using ^{7}Be to study the processes of the interrill and rill erosion on the slope during individual rainfall event is accurate and advantageous. But more works are required to apply the approach described here to investigate the temporal process of deposition in the foot area.

5. Acknowledgment

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